

LETTER TO THE EDITOR

Narrow He II emission in star-forming galaxies at low metallicity

Stellar wind emission from a population of very massive stars

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ABSTRACT

Context. In a recent study, star-forming galaxies with He II $\lambda 1640$ emission at moderate redshifts between 2 and 4.6 have been found to occur in two modes that are distinguished by the width of their He II emission lines. Broad He II emission has been attributed to stellar emission from a population of evolved Wolf-Rayet (WR) stars. The origin of narrow He II emission is less clear but has been attributed to nebular emission excited by a population of very hot Pop III stars formed in pockets of pristine gas at moderate redshifts.

Aims. We propose an alternative scenario for the origin of the narrow He II emission, namely very massive stars (VMS) at low metallicity (Z), which form strong but slow WR-type stellar winds due to their proximity to the Eddington limit.

Methods. We estimated the expected He II line fluxes and equivalent widths based on wind models for VMS and Starburst99 population synthesis models and compared the results with recent observations of star-forming galaxies at moderate redshifts.

Results. The observed He II line strengths and equivalent widths are in line with what is expected for a population of VMS in one or more young super-clusters located within these galaxies.

Conclusions. In our scenario the two observed modes of He II emission originate from massive stellar populations in distinct evolutionary stages at low Z ($\sim 0.01 Z_{\odot}$). If this interpretation is correct, there is no need to postulate the existence of Pop III stars at moderate redshifts to explain the observed narrow He II emission. An interesting possibility is the existence of self-enriched VMS with similar WR-type spectra at extremely low Z . Stellar He II emission from such very early generations of VMS may be detectable in future studies of star-forming galaxies at high redshifts with the James Webb Space Telescope (JWST). The fact that the He II emission of VMS is largely neglected in current population synthesis models will generally affect the interpretation of the integrated spectra of young stellar populations.

Key words. Stars: Wolf-Rayet – stars: mass-loss – stars: Pop III – galaxies: starburst – galaxies: stellar content – galaxies: star clusters: general.

1. Introduction

A fundamental question in Astronomy is the question of the sources of the “First Light” ending the Cosmic Dark Ages and beginning the process of reionisation. The James Webb Space Telescope (JWST) promises direct access to this critical period via observations of the first star-forming galaxies at redshifts $z \gtrsim 10$. Dual Ly α $\lambda 1216$ and He II $\lambda 1640$ emission is believed to be the main indicator of the first (Pop III) stars formed from pristine gas in these objects (e.g. Johnson et al. 2009). The reason is that only at extremely low metallicities ($Z \lesssim 10^{-5}$), young massive stars are believed to be hot enough to excite He II in their surrounding H II regions (e.g. Schaerer 2002, 2003). The investigation of star-forming galaxies with He II emission at moderate redshifts, which are accessible with current ground-based instrumentation, is thus an important preparation for future studies of the first star-forming galaxies with the JWST.

Such a study has recently been performed by Cassata et al. (2013), who identified different groups of He II emitters with narrow and broad emission lines in a sample of star-forming galaxies at redshifts $2 < z < 4.6$. While the broad emission is usually attributed to stellar emission from Wolf-Rayet (WR) stars, Cassata et al. interpreted the narrow emission as being due to ionising radiation from Pop III stars that must have formed in

pockets of residual pristine gas at relatively low redshift, or a stellar population that is rare at $z \sim 0$ but more common at $z \sim 3$.

In this letter we discuss the possibility that the narrow He II emission might also be of stellar origin. To this purpose we discuss in Sect. 2 how the spectral properties of WR-type emission line stars are expected to change at low Z , estimate the expected line shapes and fluxes in Sect. 3, and compare our results with the observations of Cassata et al. in Sect. 4. Conclusions are drawn in Sect. 5.

2. He II emission from WR stars at different metallicities Z

The emission-line spectra of WR stars are formed in their strong, optically thick stellar winds. As a result of the large optical depth of these winds, ions like He III recombine already within the wind, leading to recombination cascades with strong emission lines between excited levels of the subordinate ions. Prominent examples are He II $\lambda 1640$ and C IV $\lambda 1550$ in the UV, and He II $\lambda 4686$ and C IV $\lambda 5808$ in the optical wavelength range. The width of the emission lines is mainly determined by the terminal wind speed v_{∞} of the stellar wind. To understand why we naturally expect two populations of WR stars with broad and narrow emission lines at low Z , we need to discuss the origin of the different types of WR-type stellar winds.

2.1. WR populations in the Galaxy and LMC

Comprehensive studies of the local population of WR stars of the nitrogen sequence (WN stars) have been performed for the Galaxy by Hamann et al. (2006) and for the Large Magellanic Cloud (LMC) by Hainich et al. (2014). Both works identified two different groups of WN stars. The first group are classical WN stars with H-poor/H-free surface compositions and hot temperatures up to 140 kK, in agreement with a core He-burning evolutionary stage. The second group are the so-called WNh stars with relatively H-rich surface compositions and cooler temperatures, in agreement with a core H-burning evolutionary stage. The WNh stars are further characterised by remarkably high luminosities in excess of $\sim 10^{5.9} L_{\odot}$, while the group of classical WN stars has luminosities below this value.

The dividing luminosity at roughly $10^{5.9} L_{\odot}$ suggests that the classical WN stars are core He-burning objects in a post-red supergiant (post-RSG) phase. This picture is further supported by the work of Sander et al. (2012), who found that the WR stars of the carbon sequence (WC stars), which are showing the products of He-burning at their surface, form a natural succession of the sequence of classical WN stars in the HR diagram.

In this work we are mainly interested in the group of WNh stars with luminosities in the range $10^{5.9} L_{\odot} \lesssim L \lesssim 10^{6.9} L_{\odot}$ (cf. Hamann et al. 2006; Crowther et al. 2010; Hainich et al. 2014; Bestenlehner et al. 2014). The HRD positions of these objects suggest that they are very massive stars (VMS) with initial masses in excess of $\sim 100 M_{\odot}$, and reaching up to $300 M_{\odot}$ (cf. Vink et al. 2015). In their LMC sample, Hainich et al. (2014) found 12 % of all putatively single WN stars in the WNh stage. Combined with their high luminosities, this suggests that WNh stars have substantial impact on the integrated He II emission of star-forming galaxies.

2.2. WR mass loss at low metallicities Z

Observational evidence for a Z -dependence of WR mass-loss has been found by comparisons of the sample of WC stars with known distances in the Galaxy and LMC by Gräfener et al. (1998) and Crowther et al. (2002). In the following, we invoke the results of theoretical studies to understand how the properties of WR stars are expected to change over a broad range of Z .

The winds of classical WR stars have been modelled by Gräfener & Hamann (2005) (for early WC subtypes) and Vink & de Koter (2005) (for late WC and WN subtypes). Although there are still problems to reproduce the winds of intermediate spectral subtypes (cf. Gräfener & Hamann 2005), these works suggest that the winds of WR stars are radiatively driven, predominantly by millions of spectral lines of the iron-group elements. As a consequence, the mass-loss rates of WR stars are expected to depend on the environment metallicity Z (Vink & de Koter 2005).

The winds of luminous WNh stars have been modelled by Gräfener & Hamann (2008) and Vink et al. (2011). These works suggest that the proximity to the Eddington limit plays a key role for the formation of WR-type stellar winds. This has been further supported in systematic studies of samples of VMS in young clusters by Gräfener et al. (2011) and Bestenlehner et al. (2014). According to Gräfener & Hamann (2008), Eddington factors of the order of $\Gamma_e \approx 0.5$ are required to initiate WR-type stellar winds at solar metallicity Z_{\odot} (here $\Gamma_e = (\chi_e L)/(4\pi c G M)$ denotes the classical Eddington factor that is defined with respect to the opacity of free electrons χ_e). The required Eddington fac-

tors suggest that the masses of WNh stars are higher than those of core He-burning stars, meaning that WNh stars are indeed VMS in the phase of core H-burning.

How does the spectral appearance of the two groups of WR stars change at low metallicities? As a result of their dependence on the iron-group opacities, the winds of classical WR stars are expected to be weaker at low Z (Vink & de Koter 2005), resulting in significantly weaker emission lines (Crowther & Hadfield 2006). However, the situation is slightly different for WC stars because their surfaces are substantially self-enriched with the products of He-burning, namely C, O, and most likely Ne and Mg. According to Vink & de Koter (2005), these elements gain in importance for $Z \lesssim 0.1 Z_{\odot}$, and may even dominate WR wind driving for $Z \lesssim 10^{-3} Z_{\odot}$. WC stars may thus be the main source of broad He II emission from classical WR stars at low Z . Because of the high carbon abundances of WC stars, this emission will most likely be accompanied by strong C IV emission.

For the group of very massive WNh stars, the dependence on the environment metallicity Z has been discussed by Gräfener & Hamann (2008). According to their models, the proximity to the Eddington limit is mandatory to support WR-type winds in this regime. The required Eddington factors increase for decreasing metallicity, from $\Gamma_e \approx 0.5$ for $Z = Z_{\odot}$, to $\Gamma_e \approx 0.85$ for $Z = 0.01 Z_{\odot}$. As a consequence, the resulting effective escape velocities decrease, and very low terminal wind velocities of only few 100 km/s are predicted for WNh stars in this regime. At the same time, the mass-loss rates do not change significantly, resulting in significantly higher wind densities and much stronger and narrower WR emission lines than for classical WR stars. Very massive WNh stars at low Z may thus be the sources of the narrow He II emission observed by Cassata et al. (2013). In contrast to classical WC stars, they have very low carbon abundances and are not expected to show detectable C IV emission.

3. Expected He II emission from populations of VMS

Because of their short lifetimes (2-3 Myr), VMS are predominantly found in young massive clusters. To estimate the line fluxes expected from populations of VMS at cosmological distances, we start with an examination of young massive clusters in our neighbourhood and their stellar He II emission in Sect. 3.1 and extrapolate our results to low Z in Sect. 3.2.

3.1. VMS in young massive clusters

Wofford et al. (2014) recently found evidence for He II emission from VMS in the nearby starburst galaxy NGC 3125 with roughly LMC metallicity. For the young cluster A1 they had to invoke a population of VMS to explain the large observed He II equivalent width ($EW(\text{He II}) \sim 7 \text{ \AA}$, cf. also Chandar et al. 2004) as the cluster is too young (3-4 Myr) to host evolved WR stars. Based on different UV extinction corrections, they determined an intrinsic He II line luminosity in the range $\log(L_{\text{He II}}) = 39.1 \dots 40.0$ (in erg/s) and a cluster mass of $\log(M_{\text{cl}}/M_{\odot}) = 5.1 \dots 5.9$.

To investigate whether VMS can account for the large $EW(\text{He II})$, we also investigated R136 in the centre of 30 Dor of the LMC, the most prominent starburst-like cluster in our neighbourhood that is spatially resolved. Using the integrated IUE spectrum of the central 5 pc from Vacca et al. (1995), we measured a similarly high $EW(\text{He II}) \sim 5 \text{ \AA}$ for this object.

For the sum of the seven known WNH stars in this region (five WN5h, one WN6(h), and one WN9ha; cf. Crowther et al. 2010), we estimate in total $\log(L_{\text{He II}}) \approx 38.6$. This estimate is based on a synthetic model for the LMC WN5h star VFTS 682 from Bestenlehner et al. (2011) with $\log(L/L_{\odot}) = 6.5$ and $\log(L_{\text{He II}}) = 37.5$, which was scaled to the total luminosity of the seven objects ($\log(L/L_{\odot}) = 7.58 \pm 0.03$, as obtained from Crowther et al. 2010, Hainich et al. 2014, and Bestenlehner et al. 2014). We note that this value is uncertain as for some of the stars different luminosities have been obtained in different works, and one of the stars, Mk 34, is a known binary.

To estimate the intrinsic continuum flux, we used Starburst99 models (Leitherer et al. 1999) that are similar to those of Wofford et al. (2014, cf. their Sect. 3.5) but for $Z = 0.008$. For a cluster mass of $\log(M_{\text{cl}}/M_{\odot}) \approx 4.7$ (Doran et al. 2013)¹ and an age of 2–4 Myr, we obtain a continuum flux $\log(L_{\text{UV}}) \approx 37.74$ (in $\text{erg s}^{-1} \text{Å}^{-1}$). Together with our estimate of $\log(L_{\text{He II}}) \approx 38.6$, this results in $\text{EW}(\text{He II}) \approx 7 \text{ Å}$, in good agreement with the observations of R 136 and NGC 3125-A1. We note that the intrinsic continuum flux estimated by Vacca et al. (1995) is even lower ($\log(L_{\text{UV}}) \approx 37.33$), which may be attributed to uncertainties in the UV extinction and the precise pointing of their observations.

We conclude that the He II emission of very massive WNH stars at $Z \approx Z_{\text{LMC}}$ is probably strong enough to explain the observed strength of the He II emission of NGC 3125-A1 and R 136. In the following, we use the approximate average luminosity of the seven WNH stars in R 136 to define a representative luminosity of $\log(L_{\text{WN5h}}/L_{\odot}) = 6.7$. With the numbers above, we then obtain

$$\log(L_{\text{He II}}/(\text{erg/s})) = \log(N_{\text{WN5h}}) + 37.7, \quad (1)$$

where N_{WN5h} denotes the equivalent number of WN5h stars.

The observed He II line widths (FWHM) lie in the range of 1000–1400 km/s for NGC 3125-A1 (Chandar et al. 2004; Wofford et al. 2014) and ~ 2500 km/s for R 136. The individual WN5h stars in R 136 have a similar spectral morphology as VFTS 682, for which we estimate FWHM ~ 2000 km/s. The variations in the observed FWHM may indicate that the real stellar populations are more heterogeneous than we assumed in our simplified approach.

3.2. He II emission at low Z

To estimate $L_{\text{He II}}$ for WNH stars at low Z , we computed synthetic UV spectra using the wind models of Gräfenner & Hamann (2008). To obtain a more realistic FWHM, we used a line broadening velocity of 10 km/s instead of the artificially enhanced value of 100 km/s in the original work. In Fig. 1 we show three models with $Z = Z_{\odot}$, $0.1 Z_{\odot}$, and $0.01 Z_{\odot}$ (cf. model grid 2 in Table 2 of Gräfenner & Hamann 2008). For these models, Γ_e has been adjusted to reproduce very similar mass-loss rates for all three metallicities². As discussed in Sect. 2.2, the models with low Z have lower terminal wind velocities v_{∞} and thus higher wind densities. This leads to stronger and narrower He II emission at lower Z (cf. Fig. 1). The resulting line fluxes and FWHM are indicated in Fig. 1. We note that the wind models seem to underestimate v_{∞} at $Z = Z_{\odot}$ (cf. the discussion in Gräfenner & Hamann 2008). The important point is thus the predicted qualitative behaviour, that is, the strong decrease of v_{∞} vs. Z .

¹ Doran et al. used the same Kroupa (2001) IMF as in this work.

² As the luminosities and surface abundances are kept fixed, this change in Γ_e translates into different stellar masses M for each object.

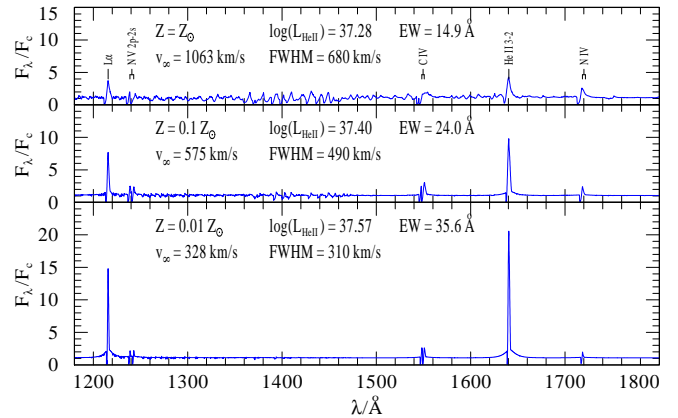


Fig. 1. Synthetic UV spectra for different metallicities Z from wind models for WNH stars from Gräfenner & Hamann (2008). The presented models are computed for a luminosity of $\log(L/L_{\odot}) = 6.3$, a stellar temperature $T_{\star} = 44.7$ kK, and have very similar mass-loss rates ($\sim 1.8 \times 10^{-5} M_{\odot} \text{yr}^{-1}$). The given He II line luminosities have only been determined for the narrow-emission components of the He II line profiles. Measurement errors for the given $L_{\text{He II}}$, FWHM, and EW probably amount to $\sim \pm 0.05$ dex (or $\pm 10\%$).

The He II line profiles in Fig. 1 consist of a narrow emission component, a comparatively weak blue-shifted P-Cygni absorption, and broad line wings that are caused by multiple electron scattering of line photons in the dense ionised wind. In addition to the iron forest between 1300 and 1500 Å, which is most prominent at high Z , the spectra show C IV, N IV, and N V features whose strength decreases for lower Z . We note that the models have been computed for an N-enriched surface composition, which will affect the relative strength of the C IV vs. N IV and N V features. Furthermore, the resulting He II line fluxes will depend on the adopted stellar temperature T_{\star} .

For low metallicities $Z = 0.1$ and 0.01 , we find He II line luminosities of the order of $\log(L_{\text{He II}}) \approx 37.5$ for a given stellar luminosity of $\log(L/L_{\odot}) = 6.3$. Adopting the same representative stellar luminosity as in Eq. 1, we obtain

$$\log(L_{\text{He II}}/(\text{erg/s})) = \log(N_{\text{WNh, lowZ}}) + 37.9, \quad (2)$$

that is, a slightly higher value than the one that we obtained for LMC metallicity.

While $L_{\text{He II}}$ increases for lower Z , the strength of the observable metal lines decreases. Most notably, all metal lines are substantially weaker than He II and will not be detectable in the integrated spectra of He II emitting galaxies, as observed by Cassata et al. (2013).

We conclude that WNH stars at low Z can produce narrow He II emission with similar or slightly stronger line fluxes than those discussed in Sect. 3.1 if the high required Eddington factors Γ_e can be maintained. Theoretically, high effective Γ_e are indeed expected due to increased stellar rotation rates at low Z (e.g., Meynet & Maeder 2002). Adopting similar relative numbers and luminosities of WNH stars as in Sect. 3.1, we would thus expect similar or slightly higher line fluxes and EWs than those discussed in Sect. 3.1 for young starbursts at low Z .

We also note that rotating massive stars in extremely metal-poor environments ($Z \sim 10^{-5} \dots 10^{-8} Z_{\odot}$) are expected to reveal primary nitrogen with mass fractions of about 1% at their surface (Yoon & Langer 2005; Meynet et al. 2006). Gräfenner & Hamann (2008) showed that such self-enriched objects can develop very similar winds as WNH stars at low metal-

licity (roughly corresponding to $Z \sim 0.02 Z_{\odot}$). We thus expect that even very early stellar generations can contain WNH stars with similar spectral properties as discussed here. For Pop III stars with zero metal content, Ekström et al. (2008) showed that qualitatively different internal mixing properties can prevent strong self-enrichment, that is, their mass-loss properties may be different (but cf. also the discussion in Vink & de Koter 2005).

4. Narrow He II emission in star-forming galaxies at moderate redshifts

A systematic study of star-forming galaxies with He II emission at moderate redshifts has been performed by Cassata et al. (2013), based on data from the VIMOS VLT Deep Survey (VVDS; Le Fèvre et al. 2005). In the total VVDS sample of ~ 45000 galaxy spectra, Cassata et al. found 277 star-forming galaxies with secure redshifts in the range $2 < z < 4.6$, of which 39 show He II $\lambda 1640$ in emission. They divided this sample into four groups of 11 objects with narrow He II lines, 13 objects with broad He II lines, 12 possible He II emitters, and 3 AGN, to distinguish between high-velocity outflows of WR stars, AGN, or supernova-driven winds, and the narrow nebular emission that is expected for Pop III stars.

Cassata et al. found that narrow and broad emitters show qualitatively different spectra. In particular, they found that only broad He II emitters (with $\text{FWHM}(\text{He II}) \geq 663 \text{ km/s}$) show indications of underlying P-Cygni type C IV $\lambda 1550$ emission. As we discussed in Sect. 2.2, this emission is most likely a signature of stellar-wind emission from classical WR stars, predominantly originating from WC subtypes at low Z . In the group of 11 narrow emitters, they only found two such cases, in line with our prediction of very weak C IV emission for WNH stars at low Z . Our predicted $\text{FWHM}(\text{He II})$ for such objects in Sect. 3.2 is clearly within the limit for narrow emitters from Cassata et al., even if we take possible uncertainties (up to a factor of ~ 2) into account.

Excluding AGN, Cassata et al. found He II line luminosities in the range $\log(L_{\text{He II}}) \approx 40 \dots 41.5$, and EWs of $\approx 1 \dots 7 \text{ \AA}$. They noted that, based on the predicted nebular He II emission for Pop III objects from Schaerer (2003), the star-formation rates required to produce the observed line fluxes are about two orders of magnitude lower than those determined from the spectral energy distribution (SFR_{sed}).

Here we furthermore note that the majority of narrow He II emitters is found at the bottom of the He II luminosity distribution in a very narrow range of $\log(L_{\text{He II}}) \approx 40 \dots 40.3$ (cf. Fig. 10 in Cassata et al. (2013)). This low-luminosity group is additionally restricted to the lowest redshifts of $z \approx 2.0 \dots 2.5$. This implies that these objects are near the detection limit. Only three objects are located outside the low-luminosity group, with $\log(L_{\text{He II}}) \approx 41.0 \dots 41.5$, and $z = 2.5 \dots 4.0$.

The observed line fluxes for the low-luminosity group are remarkably similar to our expectations for massive young super-clusters with $M_{\text{cl}} \sim 10^6 M_{\odot}$ at low Z . Clusters in this mass range are near the top end of the cluster initial mass function ($\sim 2 \times 10^6 M_{\odot}$), as determined for instance by Bastian (2008) for interacting galaxies and luminous IR galaxies. They may thus be the most luminous He II sources of this kind. For comparison, the observed continuum fluxes $\log(L_{\text{UV}}) = \log(L_{\text{He II}}/\text{EW}(\text{He II})) \approx 39.2 \dots 40.3$ are similar to or higher than the Starburst99 prediction of $\log(L_{\text{UV}}) \approx 39.04$ for a cluster with $10^6 M_{\odot}$ and an age of 2-4 Myr at low $Z = 0.0004$. Test computations for galaxies with continuous SFRs at the same metallicity suggest

$L_{\text{UV}} \lesssim 40.2 + \log(\text{SFR}/(M_{\odot} \text{ yr}^{-1}))$, meaning that the host galaxies could provide a substantial contribution to the observed continuum.

In our scenario, the continuum of a star-forming host galaxy could easily become so bright that it would prevent the detection of He II. The target selection by Cassata et al. may thus be responsible for picking the most extreme and recent starburst events at low Z that are located in host galaxies with continua weak enough to enable the detection of He II. The latter point places strong constraints on the continuum flux, which may be the reason for the narrow range of observed i-band magnitudes ($23.45 \dots 24.63 \text{ mag}_i$) compared to the wide range of derived $\text{SFR}_{\text{sed}} \approx 1 \dots 10^3 M_{\odot} \text{ yr}^{-1}$ of Cassata et al. (cf. their Table 2).

5. Conclusions

We discussed a new scenario for the origin of narrow He II emission in star-forming galaxies at moderate redshifts, based on predictions of strong WR-type stellar winds with low terminal wind speeds for very massive stars (VMS) at low metallicities ($Z \sim 0.01 Z_{\odot}$). We estimated the expected He II emission and found that it is in line with recent observations by Cassata et al. (2013). In our scenario the observed emission originates from a population of VMS in one or more young super-clusters located within a variety of star-forming galaxies at low Z . This scenario is in accordance with the observed line fluxes and EWs, the large observed spread of star-formation rates, and the different C IV profiles of the narrow and broad emitters.

If our interpretation is correct, the narrow and broad He II emitters identified by Cassata et al. both originate from massive stellar populations at low Z in distinct evolutionary stages, and there is no need to invoke the existence of Pop III stars at moderate redshifts to explain the observed narrow He II emission. The fact that the emission of VMS is largely neglected in current population synthesis models will generally affect the interpretation of the integrated spectra of young stellar populations (cf. also Wofford et al. 2014).

Finally, we note that the same argumentation will hold for rotating VMS at extremely low Z ($\sim 10^{-5} \dots 10^{-8} Z_{\odot}$), for which similarly strong winds are predicted as a result of the self-enrichment with primary nitrogen. The He II emission from such very early stellar generations of VMS may be detectable in future studies of star-forming galaxies at high redshifts with the JWST.

References

- Bastian, N. 2008, MNRAS, 390, 759
- Bestenlehner, J. M., Gräfener, G., Vink, J. S., et al. 2014, A&A, 570, A38
- Bestenlehner, J. M., Vink, J. S., Gräfener, G., et al. 2011, A&A, 530, L14
- Cassata, P., Le Fèvre, O., Charlot, S., et al. 2013, A&A, 556, A68
- Chandar, R., Leitherer, C., & Tremonti, C. A. 2004, ApJ, 604, 153
- Crowther, P. A., Dessart, L., Hillier, D. J., Abbott, J. B., & Fullerton, A. W. 2002, A&A, 392, 653
- Crowther, P. A. & Hadfield, L. J. 2006, A&A, 449, 711
- Crowther, P. A., Schnurr, O., Hirschi, R., et al. 2010, MNRAS, 408, 731
- Doran, E. I., Crowther, P. A., de Koter, A., et al. 2013, A&A, 558, A134
- Ekström, S., Meynet, G., Chiappini, C., Hirschi, R., & Maeder, A. 2008, A&A, 489, 685
- Gräfener, G. & Hamann, W.-R. 2005, A&A, 432, 633
- Gräfener, G. & Hamann, W.-R. 2008, A&A, 482, 945
- Gräfener, G., Hamann, W.-R., Hillier, D. J., & Koesterke, L. 1998, A&A, 329, 190
- Gräfener, G., Vink, J. S., de Koter, A., & Langer, N. 2011, A&A, 535, A56
- Hainich, R., Rühling, U., Todt, H., et al. 2014, A&A, 565, A27
- Hamann, W.-R., Gräfener, G., & Liermann, A. 2006, A&A, 457, 1015
- Johnson, J. L., Greif, T. H., Bromm, V., Klessen, R. S., & Ippolito, J. 2009, MNRAS, 399, 37

- Kroupa, P. 2001, *MNRAS*, 322, 231
- Le Fèvre, O., Vettolani, G., Garilli, B., et al. 2005, *A&A*, 439, 845
- Leitherer, C., Schaerer, D., Goldader, J. D., et al. 1999, *ApJS*, 123, 3
- Meynet, G., Ekström, S., & Maeder, A. 2006, *A&A*, 447, 623
- Meynet, G. & Maeder, A. 2002, *A&A*, 390, 561
- Sander, A., Hamann, W.-R., & Todt, H. 2012, *A&A*, 540, A144
- Schaerer, D. 2002, *A&A*, 382, 28
- Schaerer, D. 2003, *A&A*, 397, 527
- Vacca, W. D., Robert, C., Leitherer, C., & Conti, P. S. 1995, *ApJ*, 444, 647
- Vink, J. S. & de Koter, A. 2005, *A&A*, 442, 587
- Vink, J. S., Heger, A., Krumholz, M. R., et al. 2015, *Highlights of Astronomy*, 16, 51
- Vink, J. S., Muijres, L. E., Anthonisse, B., et al. 2011, *A&A*, 531, A132
- Wofford, A., Leitherer, C., Chandar, R., & Bouret, J.-C. 2014, *ApJ*, 781, 122
- Yoon, S.-C. & Langer, N. 2005, *A&A*, 443, 643